AN INTENSE ION SOURCE FOR H^- CYCLOTRONS

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Summary

An H^- ion source, employing multicusp plasma confinement and a magnetic filter to enhance volume H^- production, has been developed for the TRIUMF cyclotron. The source was designed to operate in a dc mode, to have a long filament lifetime and to provide an intense H^- beam of low emittance. Unlike the PIG ion source, the emittance could be easily scaled without affecting the current density to match the acceptance of the cyclotron. The source design, operating characteristics, beam quality measurements and initial operating experience with the TRIUMF cyclotron are described.

Introduction

At TRIUMF an extracted current of 140 μA at 500 MeV is routinely achieved with a current of 300 μA from the Ehlers' type PIG H^- source.[1] At this intensity the PIG source requires a weekly filament change. In terms of accelerator acceptance the source can reliably provide up to ~800 μA of useful beam, but operation at this level would require source maintenance every two days. For this reason, and because 800 μA will be insufficient to reach our goal of 500 μA at 500 MeV, a program was undertaken to develop a new source which meets the TRIUMF brightness requirements.

Several laboratories are investigating multicusp plasma generators as volume H^- ion sources for neutral beam injection in applications with fusion plasmas and for particle accelerators.[2-5] For cyclotrons these sources have several attractive features: namely, having a high brightness, stable and quiescent output and being robust and reliable, requiring little maintenance. Furthermore, the output beam is axially symmetric, significantly simplifying beam transport. Although in terms of power, volume production is less efficient than surface conversion,[6] the former mechanism produces a much brighter beam and, furthermore, requires no cesium. Voltage breakdown of the accelerating system and other reliability problems resulting from cesium contamination are therefore avoided.

We describe here the dc source developed and installed at TRIUMF and present some measurements of its performance.

Source Description

The 'cusp' or 'bucket' source is basically a bucket of plasma confined by a magnetic field created by rows of permanent magnets. In the filtered H^- cusp source the plasma is divided by a 'magnetic filter' into two regions of relatively hot and cold electrons.[2] The H^- ions are created in the cold region; this results in a beam of very good brightness. Moreover, the filter field tends to inhibit electrons from being extracted along with the H^-. For our application the source needed development in the following areas: (1) to determine the effect of dc rather than pulsed operation, (2) to optimize the aperture size for a given desired emittance, (3) to determine the filter position resulting in the best brightness and the best ratio of H^- to electrons extracted, (4) to devise an arrangement of small dipoles around the extraction aperture which safely dumps the extracted electrons without significantly affecting the H^- beam, and (5) to determine a filament size and geometry which optimize filament lifetime.

Plasma Chamber

The development source, shown schematically in Fig. 1, is a cylindrical full-line cusp source employing 10 lines of 3.2 kG samarium-cobalt magnets deployed axially on the outside of an all-copper water-cooled plasma chamber. The plasma chamber is divided into two regions by a strong magnetic filter ($\int B \cdot d\ell$ = 0.2 kG·cm)

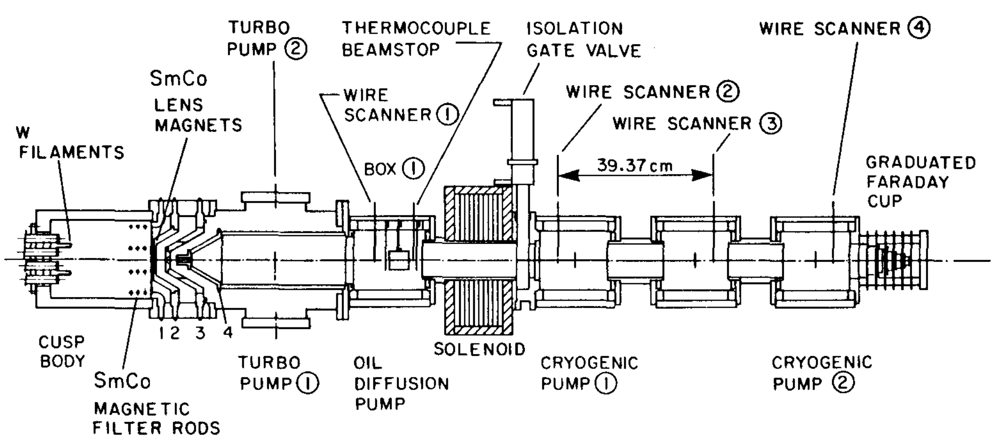

Fig. 1. Schematic diagram of the multicusp ion source, extraction system, and diagnostics geometry.

after the method of Leung et al.[2] Three sets of four holes allow the position of the filter to be varied axially in 19 mm steps with respect to the first electrode. A fourth position bringing the first electrode to within 5 mm of the filter rods is achieved by placing 1 cm spacers in the extraction electrode assembly. Water is run through the filter rods for cooling. Four lines of magnets across the back face complete the confinement of the plasma.

The chamber body is a copper cylinder (20 cm diameter by 26 cm deep inside) with 2.5 cm walls into which the Sm-Co magnets are set. Continuous operation requires water cooling which is provided by cooling passages next to each line of magnets, allowing up to 20 kW of power dissipation. Two filaments of thoriated tungsten wire (2.4 mm diameter) are mounted on the back face extending approximately 10 cm into the plasma chamber. The vacuum welds for the water-cooled filament electrodes are protected from plasma breakdown by shielding with quartz tubes. The extraction face, which is insulated from the cusp chamber body, consists of a 20 cm diameter plasma electrode with a 6.5 mm diameter extraction aperture.

Extraction Lens

The geometry of the 25 kV extraction system is shown by the cross section in Fig. 1. It is an axially symmetric four-electrode structure similar to that employed at KfK.[4] The electrical connections to the four electrodes are shown in Fig. 2. The first electrode, the end plate on the plasma chamber, is usually set at approximately +3 V with respect to the cusp body. The H^- is extracted through the 6.5 mm ϕ hole by applying a positive 3 kV potential on the second electrode. The gap between the first and second electrode is 3 mm. Permanent magnets in the first and second electrode, arranged such that they have a $\int B \cdot d\ell$ of zero, serve to sweep the simultaneously extracted electrons from the beam while giving the heavier H^- ions only a small net displacement. An additional voltage increase of ~22 kV between the second and third electrodes then brings the ion energy to 25 keV. The third electrode is held slightly positive with respect to ground in order to

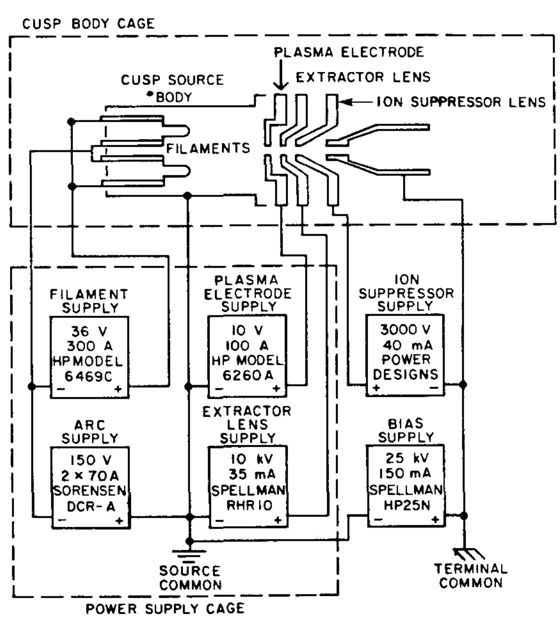

Fig. 2. Power supply connections for the source and 25 kV extraction system.

prevent backstreaming of low energy positive ions into the acceleration gap. The fourth electrode, held at ground, has a 4 cm long 12 mm diameter snout which serves as a conductance restriction for differential pumping purposes. The optimum dimensions of the extraction system were calculated using the computer code AXCEL[7] for a desired beam energy of 25 keV and current density of <10 mA/cm^2. The geometry of the extraction system can be easily modified by replacing small inserts on each electrode. The electrode material is copper and is water cooled externally.

Vacuum System

In order to reduce gas stripping in the extraction lens region and to run the source at optimum gas pressure, the extraction system was designed to allow differential pumping. Two turbopumps (310 and 340 Torr ℓ/s H_2) are located on pumping ports in the extractions system vacuum-jacket and evacuate the region between the first and fourth electrode. The last aperture in the extraction system limits the conductance into the extracted region and allows a good vacuum (1×10^{-6} Torr) to be maintained along the beam line, while a flow of 15 cc/ min of H_2 maintains a plasma chamber pressure of 7×10^{-3} Torr. A 15 cm diameter diffusion pump (3700 Torr ℓ/s air) is mounted on the first diagnostic box immediately after the extraction system and two cryogenic pumps (1000 Torr ℓ/s air) are placed in boxes 2 and 4. A gate valve between diagnostic boxes 1 and 2 allows source changes without affecting the beam line vacuum.

Diagnostics

On-line tuning of the extracted beam is accomplished with the aid of the four wire scanners shown in Fig. 1. A water-cooled thermocouple wire scanner, which measures the power profile of the beam, can be placed in any of the diagnostic boxes alongside a current wire scanner and gives an independent measurement of the beam profile. This scanner served as a check that the profile given by the faster wire scanners was not distorted by low energy electrons.

An axially symmetric graduated Faraday cup, placed downstream of the fourth diagnostic box, is used to monitor the total extracted beam current and the radial profile. A water-cooled Faraday cup, designed to measure total beam power as well as beam current, can be swung into the beam in the first diagnostic box. The beam power is measured calorimetrically by means of thermocouples placed in the water cooling circuit.

The beam emittance is determined by a method, developed at LAMPF,[8] which employs electrostatic deflecting plates located between two slits. A linear feed screw allows the precise positioning of the slit detector in the beam. A portion of the beam passes through a narrow slit (0.06 mm) into a region where two parallel plates (2.8 mm gap by 38 mm long) impose a variable transverse electric field. The beam, which passes through the second slit (0.06 mm), is detected by a Faraday cup. The plate voltage can be stepped uniformly from -500 to +500 and the cup current digitized for each voltage. The detector position is moved and a set of curves generated whose width is proportional to the angular spread of the beam at each position. A computer is then used to contour plot the beam emittance figure.

Power Supplies

A power supply scheme for achieving the 25 keV H^- beam is shown in Fig. 2. The cusp body is held at a maximum reference potential of -25 kV by a 150 mA supply. The filaments are heated by a 300 A current-regulated supply. A maximum arc power of 21 kW is

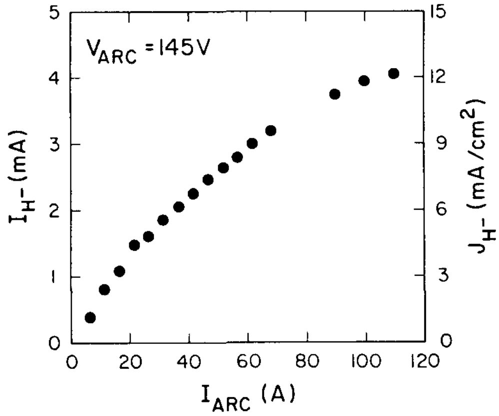

Fig. 3. Total extracted H^- beam current and density vs arc current for optimized plasma parameters at a constant arc voltage of 145 V and 25 keV extraction energy.

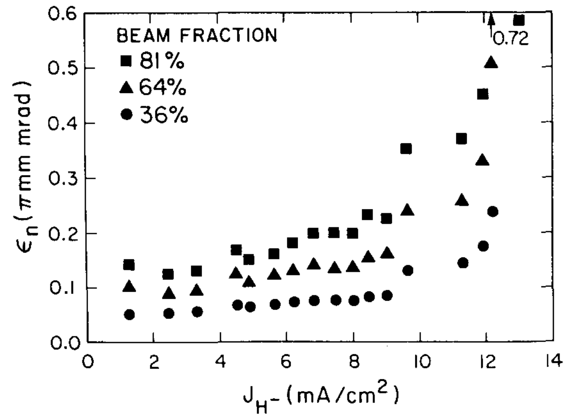

Fig. 4. Normalized beam emittance vs current density at several beam fractions for the data in Fig. 3.

provided by two 70 A - 150 V arc supplies run in a constant voltage mode. A feedback loop from the arc to the filament supply regulates the arc current. The floating supplies are controlled and monitored via an optical link.

Initial Measurements

The dependence of extracted current on source pressure displays a broad pressure optimum in agreement with observations of other sources.[2-4] At high pressure the extracted current eventually decreases. This decrease is not, however, due to stripping in the beam transport section. The current measured on the Faraday cup at the end of the beam line is ~97% of the total current measured with the cup in the first box, indicating that gas stripping in the beam line is negligible. Evidence that stripping is also unimportant in the extraction region was obtained by measuring the ratio of extracted beam current to power as a function of gas load. This measurement was done using the Faraday cup-calorimeter in the first box.

The extracted current scaled with the extraction aperture. Initial measurements with a 13.2 mm diameter aperture yielded an extracted current of ~4.1 mA compared to ~1.0 mA under similar conditions with the standard 6.5 mm aperture. The beam brightness, however, improved with the smaller aperture, probably due to a decrease in aberrations from the extraction system.

Figure 3 shows the total extracted H^- current, as measured by the graduated Faraday cup, versus arc current for an arc voltage of 145 V with all other parameters optimized. The extracted current density of 10 mA/cm^2 at an arc of 70 A - 145 V corresponds to a current of 3.1 mA at 10 kW of arc power. This is consistent with the observations of York and Stevens[3] for a similar source run at 7 Hz with a pulse duration of only 0.4 ms.

The measurements were made with the magnetic filter rods installed in the position closest to the first electrode (5 mm). This position yielded the maximum extracted H^- current while minimizing the electron contamination as evidenced by the drain currents on the second and third electrodes (typically ~15 mA).

Figure 4 shows the measured normalized beam emittance, $\varepsilon_n = \beta\gamma \times$ (phase space area), as a function of current density for the data of Fig. 3 for several beam fractions. The beam fraction f^2 is defined as the square of the fraction of beam inside the one-dimensional emittance contour.

The normalized brightness, shown in Fig. 5, is defined as $B_n = 2If^2/\varepsilon_n^2$, where I is the total beam current. The brightness is nearly constant between 3 and 10 mA/cm^2. Above 10 mA/cm^2 the apparent brightness falls because the extraction geometry is not optimized for such high current densities. The maximum measured normalized brightness for 81% beam fraction (90% contour) was 14.0 mA/(mm·mrad)^2 at a current density of 5.6 mA/cm^2. The corresponding emittance figure is shown in Fig. 6. For these data $\varepsilon_n = 0.147\pi$ mm·mrad. The normalized rms emittance is 0.038π mm·mrad. [Brightness is sometimes defined in terms of rms emittance without consideration of beam fraction. In that case the brightness is $2I/\varepsilon_{nrms}^2 \doteq 250$ mA/(mm·mrad)^2.]

The data of Fig. 6 show the qualitative features of a Maxwellian (semi-Gaussian) distribution. Moreover, four times the rms emittance contains very nearly 90% of the beam (in one dimension), and this is also true of the Maxwellian distribution.[9] The ion temperature corresponding to these data can therefore be determined[9]; it is 0.52 eV. This is in good agreement with the measured electron temperature in the extraction region[10] of 0.4±0.1 eV.

In terms of brightness the cusp source performance is very similar to that of the PIG source. [The brightness of 18 mA/(mm·mrad)^2 given in Ref. 1 for the PIG source should be compared with the f^2 = 64% brightness in Fig. 5 since it corresponds to a beam whose emittance had been cropped by a factor 1.5 mA/0.85 mA reduction in current.) However, the PIG source is very asymmetric with the two transverse emittances differing

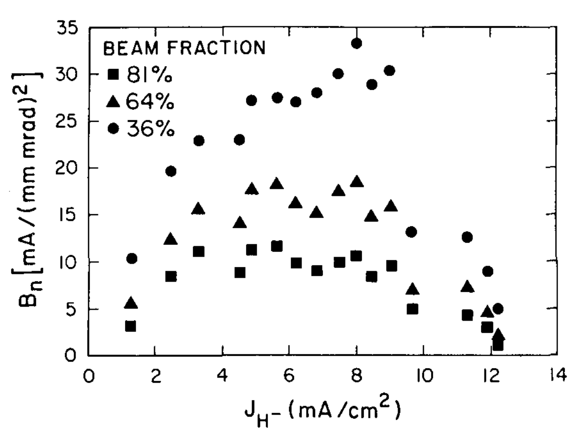

Fig. 5. Normalized brightness vs current density at several beam fractions for the data in Fig. 3.

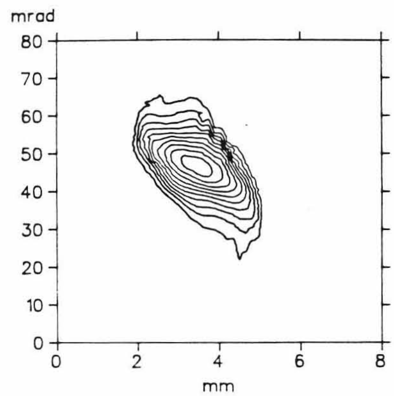

Fig. 6. Emittance figure for an extracted current of 1.85 mA. The outermost contour contains 93.4% of the beam and the other 9 contours divide the beam fraction roughly equally.

by a factor of ~4. On the other hand, the injection line can be tuned to have equal acceptances in both directions. Potentially, therefore, up to four times more current can be transported through the injection line with the cusp source than with the PIG source.

Present Status

We have moved the source to a new high voltage terminal containing a new 25 keV transport section (1.8 m long). This section is connected to a 300 kV accelerating column and a new 9.4 m beam line which transports the 300 keV beam to the existing injection line. The new section of beam line is basically a quadrupole FODO periodic section run at 90° phase advance per cell plus attendant matching quadrupoles. As in the existing injection line all quadrupoles are electrostatic.

The source has so far matched the performance of the PIG source (230 μA at 500 MeV in a pulsed mode). The current is at the present time limited by the performance of the old section of injection line.

Toroids in the injection line, used as nonintercepting current monitors, confirm the quiescent nature of the source plasma. In particular, in the frequency range up to 1 MHz, no beam oscillations greater than ~1% are apparent. With the PIG source the beam oscillates in intensity by typically 10% with a frequency of around 200 kHz.

The filament lifetime, as extrapolated from present data, is expected to be approximately one month of continuous running for an output H^- current of 1 mA. That is, at least an order of magnitude better than the filament lifetime of the PIG source.

Another potential limitation to the length of time between source servicings is the lifetime of electrode 3 (Fig. 1). Upon disassembly of the development source there was found to be a hole ~2 mm diam by ~2 mm deep in this electrode. This is determined to be due to 25 keV electrons. A new extraction geometry, in which the extraction aperture magnets have been moved closer to the beam axis, is being tested. Preliminary results show an extracted electron to H^- ratio of 1:1 with all the electrons being dumped on electrode 2 at 3 keV. Work is ongoing to optimize this geometry in terms of beam emittance.

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